

500W Stirling Engine Development

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Abstract. A successful realization of Stirling engines is conditioned by its correct conceptual design and optimal constructional and technological mode of all parts. Initial information should provide computation of real cycles of the engines. The paper presents calculation models of engine part strength, dynamics and thermodynamic cycles of the external heat supply engines. High-level FE (Finite Element), MBS (Multi Body System) or CFD (Computational Fluid Dynamics) models arising from the description of real processes which run in an external heat supply engine are used for virtual prototype of Stirling engine.

1 Introduction

The goal of the research team's work was to create a modern Stirling engine. A virtual prototype of the Stirling engine as a complex computational model of a higher level is an instrument for a successful Stirling engine design. This virtual prototype shall enable solving issues from the area of dynamics and fluid mechanics of a mechanism with high accuracy (by as much as one order) as required for further solution of control and diagnostics of a micro plant for combined production of heat and generation of power with the Stirling engine. The solution dealt with γ -modification Stirling engine with the useful output up-to 500 W [4].

2 Development Process of Stirling Engine

The development process of Stirling engine starts with an initial design of thermodynamic engine parameters. These proposals determine basic engine properties (an engine displacement, working medium etc.). However, there are still many restrictions. One of the most strictest ones is the economical aspect which has to be carefully considered.

After the main engine parameters are proposed the accent is changed to advanced CAE computational models. The development process and computational methods are presented in Figure 1. The process continues with the first prototype of the engine. The real prototype enables to validate calculation results.

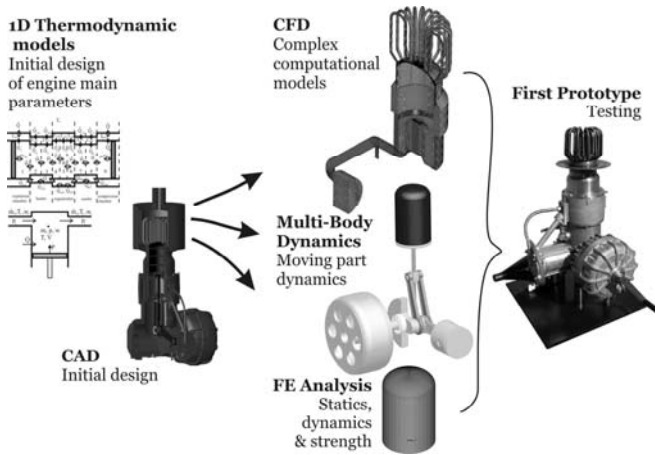


Fig. 1. Stirling engine development process

3 Stirling Engine Driving Mechanism Dynamics

Various alternatives of the crank mechanism or the rhombic mechanism are usually applied as the driving mechanism of the Stirling engine. It can also be realised as an engine with free pistons.

A centric crank mechanism has been applied for the piston and a centric crank mechanism with a crosshead has been applied for the displacer in the Stirling engine. While the issue of the dynamic balance of the driving mechanisms has been well elaborated and is based on the fact that both the geometrical and mass parameters of individual cylinder units are identical in internal combustion engines, these prerequisites are usually not met in case of the Stirling engine.

Multi-body systems can be applied as effective tools for solving Stirling engine dynamics. Multi-body systems enable solving different dynamic issues of complex systems combining rigid and flexible bodies. In the case of Stirling engine mechanisms, they can be used to find the optimum alternative for balancing the driving mechanism.

When the mechanism moves, inertial forces of different moving parts take effect, causing vibrations and must be "captured" by means of the machine seating. A virtual mechanism prototype has been created in the multi-body system and the end-point trajectory of inertial force resultant vector traced during one engine revolution running at the unit angular velocity of the crankshaft.

4 FE Analysis of Main Parts

FE computational tools enable calculations of engine part strength including fatigue calculations. Loading (forces, pressures, temperatures etc.) can be obtained from MBS or CFD results. For example, Figure 2 shows FE analysis results of displacer piston deformations for two design variants. The first version of the displacer piston includes ribs and the second one is without any ribs.

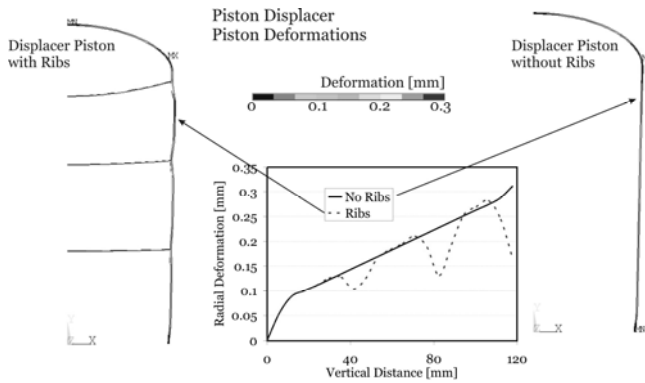


Fig. 2. FE analysis of displacer piston deformation for two variants

5 Regenerator of Stirling Engine

To use the positive effect of regenerative heat accumulation on the thermal efficiency of Stirling engine, the real regenerator should meet the following requirements:

- Heat capacity of regenerator material should be as high as possible.
- Heat conductivity of regenerator material should be as high as possible.
- For growing values of heat transfer coefficient, a temperature difference between the working gas and the regenerator material decreases; this then decreases energy losses through the heat transfer. To reach higher values of heat transfer coefficient, it is necessary to increase the velocity of working gas flow. This can be obtained through decreased sectional areas, and consequently a decreased regenerator free volume.
- The surface area for heat transfer in the regenerator should be as large as possible.
- On the other hand, a free volume of regenerator decreases pressure amplitudes and thus also the output of Stirling engine.
- Pressure losses in the regenerator should be as little as possible.

Based on the comparison of the above, mostly contradictory requirements, it is evident that at present there is no real material to meet these requirements. A search for appropriate regenerator material is therefore an optimization problem that always has to be re-solved for each particular Stirling engine.

Operational revolutions of Stirling engines are usually in the range of 900 - 3000 rpm so that time intervals for accumulation and removal of heat in the regenerator are relatively very short. Therefore the appropriate structures of regenerator should have the largest possible ratio of the surface area to the volume, and also high heat conductivity. Examples of appropriate material structures for the regenerator are shown in Figure 3.



Fig. 3. Examples of appropriate regenerator material structures

Metal materials (e.g. high-quality steel, copper or bronze) have higher heat capacity and better heat conductivity than ceramics. Therefore, the layers of fine wire netting often form the regenerators of Stirling engines. For optimization of regenerator, it is necessary to construct a sufficiently accurate computational model for determination of its heat and pressure losses.

The empirical Darcy's law has been applied for flows through porous media when the Reynolds number based on the pore size d_p is very small. The momentum equation for fluid flows passing through an isotropic media is given by

$$-\Delta p = \frac{\nu \mathbf{U}}{K}, \quad (1)$$

where p is the pore pressure, ν the fluid viscosity, and $\mathbf{U}$ the Darcy velocity. Here, Darcy velocity is taken as a superficial velocity by regarding the media as a continuum and ignoring the details of porous structures. The permeability, K , is defined as

$$K = \frac{\phi^3 d_p^2}{a(1 - \phi)^2}, \quad (2)$$

where ϕ is the porosity of porous material and a is a constant to parameterize the microscopic geometry of the porous materials.

Engineering practice requires the operation of flows in porous materials at high Reynolds number, such as those in Stirling engine regenerators. Experimental evidence showed that equation (1) was unable to describe the flows at high Reynolds number.

On the basis of experimental data, the equation (1) was gradually supplied with further members (Ergun, 1952) that extend its validity to a larger range of Reynolds numbers under a steady flow

$$-\Delta p = \frac{\nu \mathbf{U}}{K} + \frac{H \sqrt{\rho \nu |\mathbf{U}|} \mathbf{U}}{K^{3/4}} + \frac{F \rho |\mathbf{U}| \mathbf{U}}{\sqrt{K}}, \quad (3)$$

where ρ is the fluid density and the Forchheimer coefficient F is given by $F = b / \sqrt{a \phi^3}$ where b is again a constant to parameterize the microscopic geometry

of the material. The dimensionless coefficient H , like F , is a function of porosity and microscopic solid geometry. There remains a task to construct a model for unsteady flows through porous materials, which to the first-order approximation is valid over the entire ranges of time scale and Reynolds number.

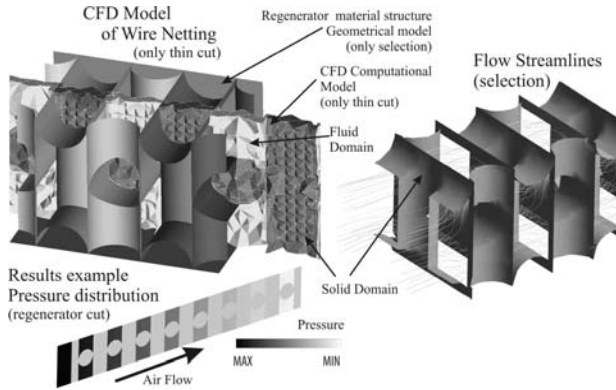


Fig. 4. CFD model and result examples of Wire Netting-type regenerator

Contemporary tools of Computational Fluid Dynamics (CFD Software) offer new possibilities of solving the problems of heat flow and transfer in Stirling engine regenerators. Figure 4 illustrates the example of wire netting-type regenerator material structure, its CFD model and examples of CFD results. Initial and boundary conditions (fluid flow velocities, temperatures etc.) for solution are obtained from CFD global model of Stirling engine.

6 Conclusion

The virtual prototypes including thermodynamic cycles or dynamics and strength of components of the Stirling engine are being created as higher-level computational models based on CFD, MBS or FEM models of physical processes occurring in real units, using only the minimum simplifying assumptions. New computational models are created after the necessary number of technical experiments is made. They will speed up the development of Stirling engines with better technical and economic parameters.

These computational models enable to compare different regenerator types like Wire Netting, Tubes, Stuffed wire mesh and Honeycomb ceramics relatively quickly. Different balancing of driving mechanism or designs of displacer pistons can be analyzed by these models as well.

Figure 5 presents the real prototype of Stirling engine with computed and measured brake power and total efficiency.

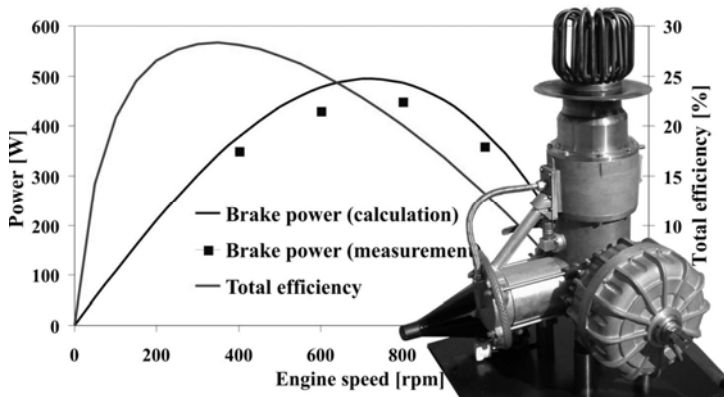


Fig. 5. Stirling engine prototype

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